Volume Title
ASP Conference Series, Vol. **Volume Number**
Author

Radial velocity monitoring of long period hot subdwarf + main sequence binaries with HERMES@Mercator

Roy H. Østensen and Hans Van Winckel

Instituut voor Sterrenkunde, K.U. Leuven, B-3001 Leuven, Belgium

Abstract. Population synthesis models predict that the majority of sdBs form through stable mass transfer leading to long period binaries. To date, about a hundred close short-period binaries with an sdB component have been found, but not a single long-period system has been established. We show preliminary results from our recent effort in determining orbits for a sample of long-period sdB systems using the HERMES spectrograph on the Mercator telescope.

1. Introduction

Binarity is a key component both in the formation and in the final evolution of stars, when expansion forces one of the companions to fill its gravitational well, and its envelope to spill over to that of the partner. Binary processes strongly influence the composition of stellar populations, and a diverse variety of evolved objects can only be explained through the direct interaction between the bloated envelope of a giant, and accretion by its companion. Such binary interactions are complex and the models invoke a number of poorly constrained parameters, such as the efficiency of envelope ejection, the physical description of the common-envelope phase, the accretion efficiency on to the companion, and many others. Observations that can constrain these model parameters are essential not just for explaining the particular systems, but for population synthesis in general, and for extrapolating to environments of various densities and metalicities as found in clusters and other galaxies.

Han et al. (2002, 2003) made a thorough binary population synthesis study of the hot subdwarfs, using all three binary formation channels that are thought to contribute significantly to the population. The three are; (1) If the subdwarf progenitor has a low mass companion, then mass transfer on the RGB is unstable, and the orbit will shrink until the envelope is ejected. The study of Maxted et al. (2001) as recently completed by Copperwheat et al. (2011) finds that ~50% of all sdB stars reside in short-period binary systems ($P_{\rm orb} < 10$ d). (2) If the companion is more massive than the subdwarf (at least at the end of mass transfer), the orbit will have expanded substantially. Such orbits are hard to measure, but the companion can be detected spectroscopically or from infra-red excess. Napiwotzki et al. (2004) found that more than a third of their sdB sample show the spectroscopic signature of main sequence (MS) companions, while Reed & Stiening (2004), using 2MASS photometry, inferred that about half of the sdBs in the field have main-sequence companions, and are therefore likely to be of this post-stable-Roche-lobe-overflow (pRLOF) type. (3) The final binary formation channel is

Table 1. Eight targets in our sample of composite hot subdwarf / main sequence systems. The spectroscopic class from various sources is given together with the visual magnitude and the number spectra we have collected so far.

Target name	Sp.Class	m_V	N.sp	References
BD–11°162	sdO+?	11.2	12	Zwicky (1957)
	sdO+G			Berger & Fringant (1980)
	sdOB+K0			Ulla & Thejll (1998)
PG 1104+243	sdB+K2	11.3	24	Ferguson et al. (1984)
	sdB+G8			Orosz et al. (1997)
Balloon 82800003	sdB+K1	11.4	16	Bixler et al. (1991)
BD+29°3070	sdOB+F	10.4	15	Berger & Fringant (1980)
	sdB+K0			Ulla & Thejll (1998)
BD+34°1543	sdB+F	9.4	13	Berger & Fringant (1980)
	sdB+G8			Ulla & Thejll (1998)
BD–7°5977	sdB+K0IV-III	10.5	17	Ulla & Thejll (1998)
				Heber et al. (2002)
Feige 80	sdO+A	11.4	21	Berger & Fringant (1980)
	sdO+G8			Ulla & Thejll (1998)
Feige 87	sdB+?	11.7	15	Jeffery & Pollacco (1998)

the merger of two low-mass white dwarfs, and has a much lower efficiency than the two other channels.

By now, ~100 sdB stars are known to reside in short period binaries, and they are providing clear constraints for common-envelope ejection models. A recent compilation can be found in Appendix A of Geier et al. (2011), but new systems are discovered at a high pace. The longest period systems are 15 and 29 days respectively (from Morales-Rueda et al. 2003). For the longer period systems very little is known. Green et al. (2001) mention a mean $\Delta v \sin i$ of 11.5 km/s from 89 observations of 19 composite binaries, and estimate periods averaging 3–4 years, but provide no details about particular systems. Here we will.

2. Observations

The observations presented here were all made with the Mercator telescope on La Palma, which is a twin of the Swiss 1.2m Euler telescope at La Silla. In November 2008 a new state-of-the-art fibre-fed ultra-stable high-resolution Echelle spectrograph was installed. This instrument, dubbed HERMES (an acronym for *High Efficiency and Resolution Mercator Echelle Spectrograph*, Raskin et al. 2011) reaches a spectral resolution, $R = 85\,000$ over a spectral range covering 3770 to 9000 Å in a single exposure, and has a peak efficiency of 28%. Being mounted in a temperature and pressure controlled environment provides the stability to ensure reliable velocity determinations over extended periods of time. A substantial fraction of the observing time on MERCATOR is dedicated to a long-term program to establish orbits of evolved binary systems. On this program we have, since the commissioning of HERMES, made regular observations of a sample of composite hot subdwarf stars. The high resolution and excellent

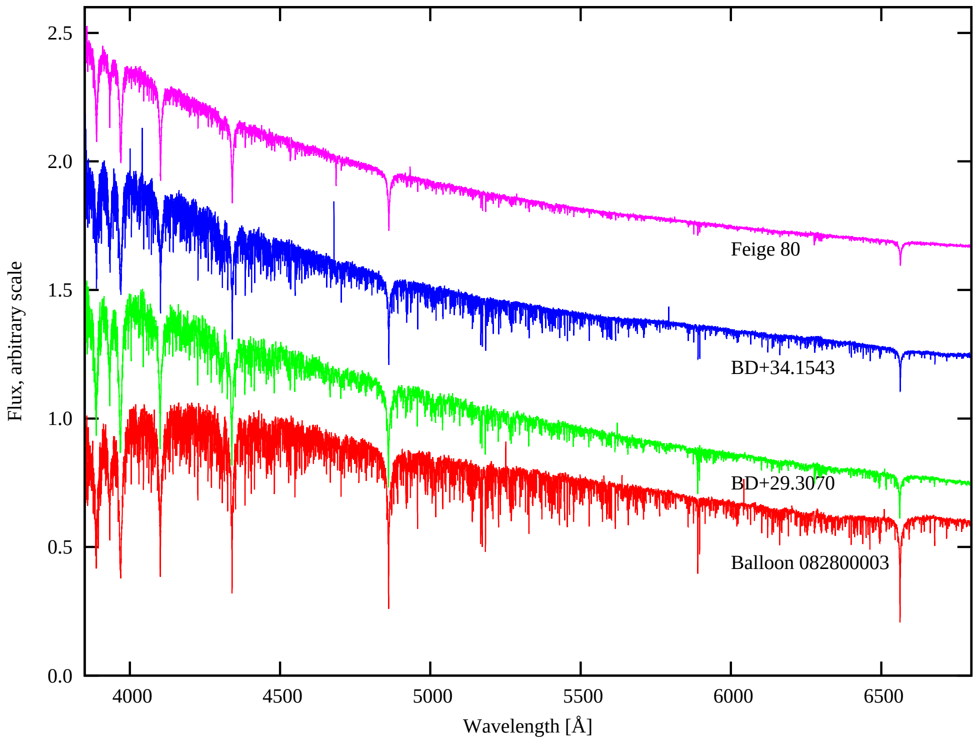

Figure 1. Single spectra for four of the targets in the sample. The resolution has been substantially degraded, and the wavelength region truncated to 3800–6800 Å for illustration purposes. The slope of each spectrum has been corrected by calibration with observations of the single sdB star Feige 66, and offset for clarity. It can be seen that the contribution from the companion varies substantially between the targets. However, even in Feige 80, where the spectrum is well dominated by the sdB component, there are sufficient lines from the MS companion for the cross-correlation to succeed in establishing precise radial velocity measurements for the cool star.

time coverage provided by HERMES will allow us to establish the periods and velocity amplitudes of even the longest period systems with very high precision.

In Table 1 we list eight stars in our sample that we have determined preliminary orbits for. The full sample contains 22 stars, but some of these have been discontinued since they were too faint to determine reliable radial velocities, and others have been inserted to replace those, but do not have a sufficiently long time base yet. The limiting magnitude for HERMES to reach an S/N useful for our method appears to be around $V = 13$, but we have focused on the stars brighter than $V = 12$ in order to use the available time most efficiently. In the table we also list the spectroscopic class from the literature and the reference for that identification. The V magnitude of the stars are also listed together with the number of spectra available for each object. This is the total number of spectra, and in some cases they are taken on the same night so that the number of points useful for period determination can be smaller.

In Figure 1 we show spectra of four of the stars up to 6800 Å. The top spectrum is Feige 80 (= PG 1317+123), and it is clearly the star where the hot component gives

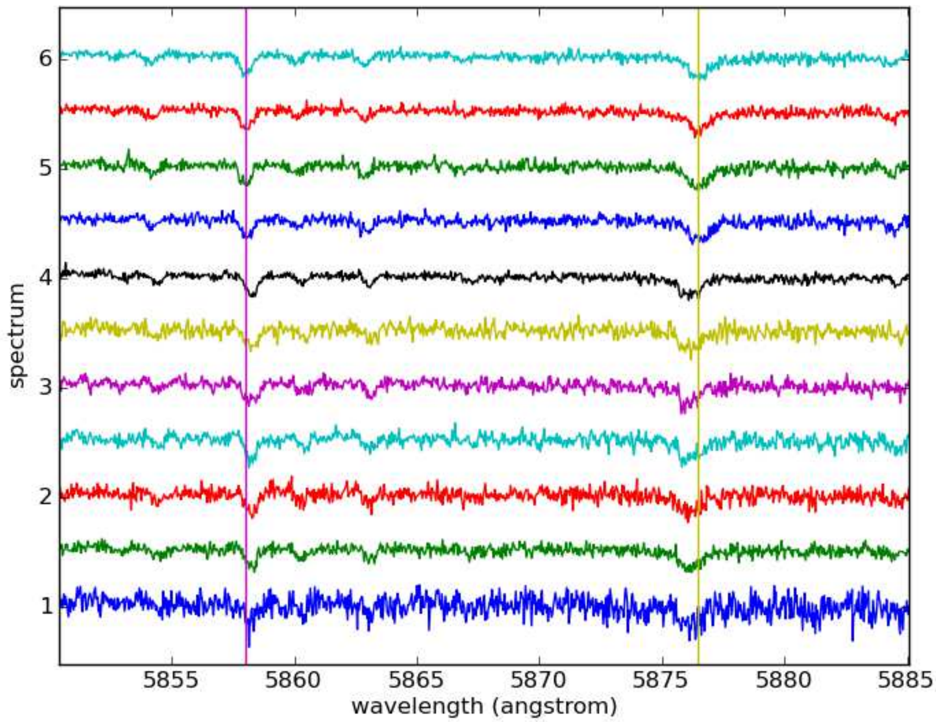

Figure 2. A small section of our spectra of BD+34°1543. The He I line from the sdB at 5876 Å is clearly seen to move in the opposite phase to that of the Ca I line at 5857 Å.

the strongest contribution to the total flux. The He II line at 4686 Å is strong and deep while He I at 4472 is quite shallow and hard to discern, making this component an sdO star, as noted already by Berger & Fringant (1980). With so little detectable He I, the temperature must be close to 50 000 K, and is therefore likely to be in the post-EHB stage of evolution. The lines from the companion, although weak, are indicative of an F–G companion, but we have not attempted to make a reliable determination of the companion classes for any of the sample objects yet. The exception on the other extreme is BD–7°5977, which is completely dominated by the deep and narrow spectral lines of a K subgiant or early RGB star (spectrum not shown).

Another clear sdO star in our sample is BD–11°162, which shows no trace of the He I 4472 line, making it even hotter than Feige 80, however, the companion is also stronger contributing about 1/3 of the flux around 6000 Å. The other objects in Figure 1 are more typical of the systems in our sample, with both stars contributing roughly equally to the flux around 6000 Å. Balloon 82800003, BD+34°1543, BD+29°3070 and Feige 87 all show the He I lines at 4472 and 5876 Å, but no detectable He II, making them sdB stars. PG 1104+243 shows both He I and He II lines, making it an sdOB star. The classifications are summarised in Table 2, together with results from the orbital analysis.

Inspection of the high-resolution spectra clearly reveals large differences in the rotational broadening of the lines from the cool companion. BD+29°3070 shows lines

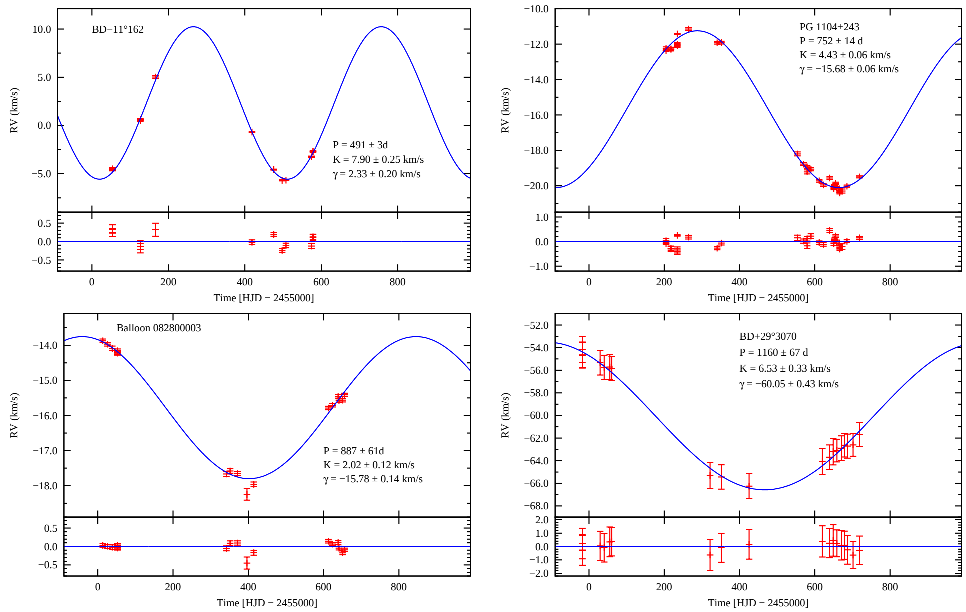

Figure 3. Thanks to the high precision of the HERMES spectrograph, the twelve observations on nine different nights of BD–11°162 are sufficient to derive a quite reliable period after just two observing seasons, as long as circular orbits are assumed. Other stars yield similarly excellent results. For BD+29°3970 the cross correlation procedure overestimates the errors since the high rotation makes the line profiles substantially non-Gaussian.

broadened by as much as 60 km/s, while most of the stars have moderately broadened lines. The subgiant component of BD–7°5977 has very sharp lines, consistent with no significant rotation, as one may expect from an expanding giant.

3. Radial velocity analysis

In Figure 2 we show a small section of the spectra that make out the sequence of observations for BD+34°1543. On the left side one can see the Ca I line at 5857 Å from the cool MS star (as well as the two weaker components of the triplet), and on the right the broader He I line at 5876 Å originating from the sdB star can be seen. The two lines are clearly moving in antiphase with each other, and the sdB would appear to have an amplitude about twice that of the F-star, as one would expect.

Up to now, we have not made any attempt at deriving radial velocities from the lines of the hot subdwarf, although in principle it should be possible for most of the targets. The results we show here are all based on cross-correlation analysis of the lines from the main sequence companion with standard templates. Due to the high number of lines available this procedure yields excellent high precision radial velocities even when the spectra are relatively low S/N. In Figure 3 and 4 we show the measurements and fits for the eight stars listed in Table 1. As one can see from the plots, all objects have rather poor sampling, and only the shortest case covers more than a full orbit, the rest showing only between half and one cycle. There is however exceptionally little scatter around

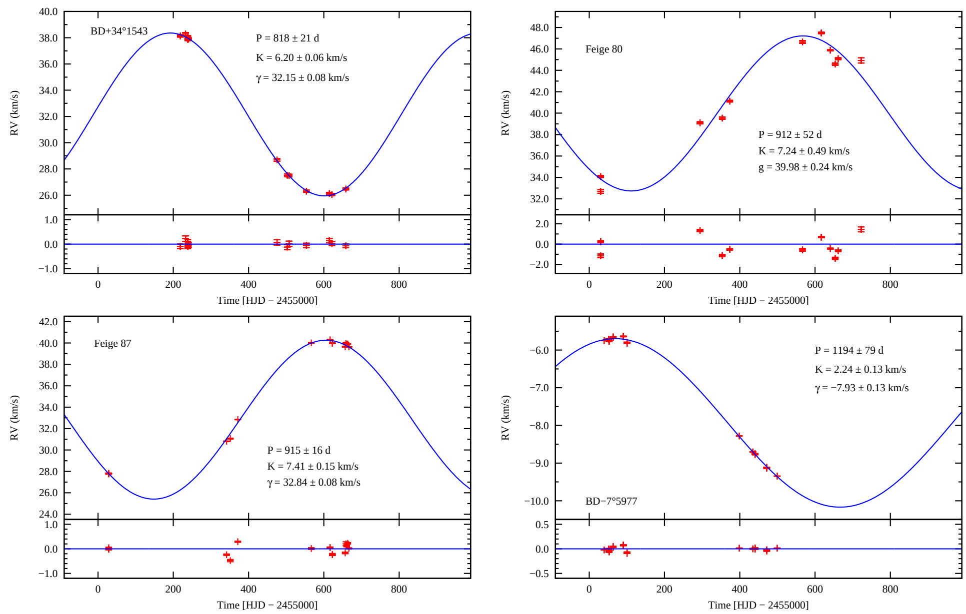

Figure 4. Same as Figure 2, for four other stars that we were able to find reasonable solutions for. For Feige 80 the residuals are significantly larger than indicated by the error bars. We have not detected anything amiss with the spectroscopy so we believe that these are real velocity variations originating on the surface of the F-star, most likely caused by stellar pulsations.

the fitted sine curves, which clearly indicates that the assumption of circular orbits as expected from binary evolution with stable mass transfer is valid.

A few of the stars, Feige 80 in particular, shows a scatter around the fitted curves that are significantly higher than the cross-correlation errors indicates. We believe that these variations are real, as they have the amplitude and periods expected for gamma Doradus type pulsations in F-stars or spots in main-sequence stars. Several examples of low amplitude photometric variability in sdB+F/G stars, consistent with these scenarios, were detected in *Kepler* targets (Østensen et al. 2011). For the particular case of BD+29°3070 the opposite is the case; the cross-correlation errors are clearly larger than expected when compared with the sine fit. This is due to the discrepancy between the rotationally broadened line profiles, and the Gaussian profiles assumed by the cross-correlation procedure.

The first object shown in Figure 3 is BD–11°162. With the errors from the cross-correlation routine being less than 0.1 km/s for all the the measurements, the fit to the RV curve is excellent. With 12 observations covering more than 500 days, it appears that we have just managed to cover a complete orbit in two observing seasons. Our solution provides an orbital period of 491 days with an RV amplitude of 7.9 km/s, as stated on the plot. This is the shortest period found in any of the stars. The next object in Figure 3, PG 1104+243, gives the second longest period (750 d). Four of the remaining objects come out with periods that are between 818 and 915 days, while two objects stand out with periods between 1100 and 1200 days. For all the stars the radial velocity amplitudes are low, between 2 and 8 km/s. Our best fit periods and velocity amplitudes are given in Table 2.

Table 2. Summary of orbital periods, velocity amplitudes for the main sequence companion and system velocities found for the sample stars. The classes given are our own estimates based on the appearance of the spectra. In the last column the rotational broadening is given. The numbers in parentheses are the estimated errors on the values. For the period and velocity amplitude the stated errors are the formal fitting errors from non-linear least square three-parameter sine fits. The rotational broadening was not fitted, but estimated by convolving a model spectrum until a reasonable agreement was achieved.

Target name	Sp.Class	m_V	Period	$K_{\rm MS}$	γ	$v_{\rm rot}\sin(i)$
BD–11°162	sdO+G	11.2	491(3)	7.9(3)	+2.3(2)	5(5)
PG 1104+243	sdOB+G	11.3	752(14)	4.43(6)	–15.68(6)	5(5)
Balloon 82800003	sdB+F	11.4	887(61)	2.0(1)	+15.8(2)	20(5)
BD+29°3070	sdOB+F	10.4	1160(67)	6.5(3)	–60.1(4)	60(5)
BD+34°1543	sdB+F	9.4	818(21)	6.20(6)	+32.15(8)	12(3)
BD–7°5977	sdB+K2III	10.5	1194(79)	2.2(1)	–7.9(1)	0(1)
Feige 80	sdO+G	11.4	912(52)	7.2(5)	+40.0(2)	15(5)
Feige 87	sdB+G	11.7	915(16)	7.4(2)	+32.8(1)	5(5)

4. Conclusions

Our long time-base spectroscopy from the Mercator telescope has revealed orbits of ~500 d and longer for eight sdB+F/G binaries (Figure 2 and 3). While pRLOF systems are expected to be found with a wide range of periods, a strong peak is predicted to be found just above 100 d (see Figure 21 of Han et al. 2003). All the systems shown in Figure 1 appear to have periods much longer than this peak, indicating that some of the parameters that govern the mass transfer process need to be adjusted.

While more than one hundred hot subdwarfs are known to exist in short-period systems, the long-period systems predicted as the outcome of stable Roche-lobe overflow on the first giant branch require extraordinary efforts to nail down. We have presented our first results from a dedicated survey to reveal the orbital periods of hot subdwarfs with main sequence companions, and the periods detected so far are far longer than the distribution predicted by Han et al. (2003), but in excellent agreement with the estimated average of 3–4 years mentioned by Green et al. (2001).

Acknowledgments. The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007–2013)/ERC grant agreement № 227224 (PROSPERITY), as well as from the Research Council of K.U.Leuven grant agreement GOA/2008/04.

Based on observations obtained with the HERMES spectrograph, which is supported by the Fund for Scientific Research of Flanders (FWO), Belgium, the Research Council of K.U.Leuven, Belgium, the Fonds National Recherches Scientific (FNRS), Belgium, the Royal Observatory of Belgium, the Observatoire de Genéve, Switzerland and the Thringer Landessternwarte Tautenburg, Germany.

References

Berger, J., & Fringant, A.-M. 1980, A&A, 85, 367

Bixler, J. V., Bowyer, S., & Laget, M. 1991, A&A, 250, 370

Copperwheat, C. M., Morales-Rueda, L., Marsh, T. R., Maxted, P. F. L., & Heber, U. 2011, ArXiv e-prints. 1103.4745

Ferguson, D. H., Green, R. F., & Liebert, J. 1984, ApJ, 287, 320

Geier, S., Hirsch, H., Tillich, A., Maxted, P. F. L., Bentley, S. J., Østensen, R. H., Heber, U., Gänsicke, B. T., Marsh, T. R., Napiwotzki, R., Barlow, B. N., & O'Toole, S. J. 2011, A&A, 530, A28+. 1103.4045

Green, E. M., Liebert, J., & Saffer, R. A. 2001, in 12th European Workshop on White Dwarfs, edited by J. L. Provencal, H. L. Shipman, J. MacDonald, & S. Goodchild , vol. 226 of Astronomical Society of the Pacific Conference Series, 192. arXiv:astro-ph/0012246

Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669. arXiv:astro-ph/0301380

Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., & Ivanova, N. 2002, MNRAS, 336, 449. arXiv:astro-ph/0206130

Heber, U., Moehler, S., Napiwotzki, R., Thejll, P., & Green, E. M. 2002, A&A, 383, 938. arXiv:astro-ph/0201096

Jeffery, C. S., & Pollacco, D. L. 1998, MNRAS, 298, 179

Maxted, P. F. L., Heber, U., Marsh, T. R., & North, R. C. 2001, MNRAS, 326, 1391. arXiv:astro-ph/0103342

Morales-Rueda, L., Maxted, P. F. L., Marsh, T. R., North, R. C., & Heber, U. 2003, MNRAS, 338, 752. astro-ph/0209472

Napiwotzki, R., Yungelson, L., Nelemans, G., Marsh, T. R., Leibundgut, B., Renzini, R., Homeier, D., Koester, D., Moehler, S., Christlieb, N., Reimers, D., Drechsel, H., Heber, U., Karl, C., & Pauli, E.-M. 2004, in Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, edited by R. W. Hilditch, H. Hensberge, & K. Pavlovski, vol. 318 of PASPC, 402

Orosz, J., Wade, R. A., & Harlow, J. J. B. 1997, AJ, 114, 317

Østensen, R. H., Silvotti, R., Charpinet, S., Oreiro, R., Bloemen, S., Baran, A. S., Reed, M. D., Kawaler, S. D., Telting, J. H., Green, E. M., O'Toole, S. J., Aerts, C., Gänsicke, B. T., Marsh, T. R., Breedt, E., Heber, U., Koester, D., Quint, A. C., Kurtz, D. W., Rodríguez-López, C., Vučković, M., Ottosen, T. A., Frimann, S., Somero, A., Wilson, P. A., Thygesen, A. O., Lindberg, J. E., Kjeldsen, H., Christensen-Dalsgaard, J., Allen, C., McCauliff, S., & Middour, C. K. 2011, ArXiv e-prints. 1101.4150

Raskin, G., van Winckel, H., Hensberge, H., Jorissen, A., Lehmann, H., Waelkens, C., Avila, G., de Cuyper, J.-P., Degroote, P., Dubosson, R., Dumortier, L., Frémat, Y., Laux, U., Michaud, B., Morren, J., Perez Padilla, J., Pessemier, W., Prins, S., Smolders, K., van Eck, S., & Winkler, J. 2011, A&A, 526, A69+. 1011.0258

Reed, M. D., & Stiening, R. 2004, PASP, 116, 506

Ulla, A., & Thejll, P. 1998, A&AS, 132, 1

Zwicky, F. 1957, Morphological astronomy (Springer)